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Stimulation of N_2O emission by conservation tillage management in agricultural lands: A meta-analysis

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ABSTRACT

Conservation tillage has been widely adopted in agricultural lands worldwide and is considered a potential strategy for climate change mitigation through enhanced carbon sequestration. However, conservation tillage may alter soil N_2O emissions, which may diminish the potential climate change mitigation benefits. Based on 212 observations from 40 publications, a meta-analysis was conducted to quantitatively assess the effects of climate regimes, initial soil properties, and type/duration of agricultural practices on soil N_2O emission following application of conservation tillage. Overall, conservation tillage significantly increased soil N_2O emission by 17.8% compared to conventional tillage. The greatest increase in N_2O emission was observed from soils in tropical climates (70.1%) experiencing short-term (29.3%) application of conservation tillage. Soil pH and clay content significantly influenced N_2O emission, while overall soil texture and soil organic carbon (SOC) were not effective predictors of soil N_2O emission following conservation tillage. According to the categorical meta-analysis, agricultural practices, including water, residue, and rotation managements and crop types, significantly affected soil N_2O emission following conservation tillage. Conservation tillage induced N_2O emissions were mitigated with rain-fed cropping systems, residue removal, crop rotation and cultivation of beans and some vegetables. Significant categorical variables affecting N_2O emission were mainly attributed to soil aeration and substrate availability, which were important factors affecting nitrification and denitrification processes. Overall, the conservation tillage induced N_2O emission factor (EF_{ad}) increased by 0.40%, suggesting an attenuation of climate change benefits from increased N_2O emission. Our meta-analysis provides a scientific basis for assessing the effects of conservation tillage on N_2O emissions and provides site-specific information to mitigate N_2O emissions associated with conservation tillage practices.

1. Introduction

Global warming attributed to the anthropogenic emissions of greenhouse gases (GHG) has increased the global temperature by ~0.89 °C in the 20th century (IPCC, 2013). Approximately 13% of total GHG emissions were contributed from agricultural lands and N_2O emission from agriculture accounted for 61% of total anthropogenic N_2O emissions (Montzka et al., 2011). The large N_2O emissions from agricultural lands are of particular concern given both its high global warming potential (GWP-N_2O = 298) relative to CH_4 (21) and CO_2 (1) and its contribution to stratospheric ozone depletion (Li et al., 2014; Hou et al., 2016).

Conservation tillage, including no-tillage and reduced tillage management, is increasingly being adopted on agricultural lands worldwide. About 10% of global arable lands, *i.e.* ~125 million hectares, are currently managed using conservation tillage (Friedrich et al., 2012). The adoption of conservation tillage has demonstrated important benefits for soil carbon sequestration in topsoil, soil erosion, soil quality and crop yields (Seta et al., 1993; Baker et al., 2007; Das et al., 2014; Powlson et al., 2014; Pittelkow et al., 2015). However, there is considerable debate concerning the effects of conservation tillage on climate change mitigation due to the highly variable effects of conservation tillage on N_2O emissions. Various studies found increase (Lognoul et al., 2017), decrease (Mutegi et al., 2010), and no differences (Guardia et al., 2016) in N_2O emissions resulting from adoption of conservation tillage practices. These inconsistent effects may be

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associated with the duration of conservation tillage practices with short-term application (< 10 years) reported to stimulate N_2O emission while long-term application (> 10 year) decreases N_2O emission (Six et al., 2010). Additionally, climate regimes and various soil properties are reported to have a strong effect on soil N_2O emission.

Soil N_2O emission primarily results from nitrification and denitrification processes in soil. Under relatively aerobic conditions, NH_4^+ is converted to NO_3^- (nitrification) along with N_2O emission by autotrophic nitrifiers, In contrast, under anaerobic conditions, heterotrophic denitrifiers convert NO_3^- to N_2O and N_2 (denitrification) (Khalil et al., 2004). Soil aeration status (e.g., O_2 availability) is a dominant factor controlling nitrification and denitrification processes and their potential N_2O production. In addition, soil physical and chemical properties, such as soil texture, pH, organic content, clay content, etc., play significant roles in N_2O emission dynamics. For instance, fine-textured soils often have higher N_2O emissions than coarse-textured soils due to slower O_2 diffusion rates leading to lower soil O_2 concentrations that favor denitrification (Pelster et al., 2012). However, other studies have shown lower N_2O emission from fine-textured soils as low gas diffusivity allowed greater time for more complete reduction of N_2O to N_2 (Weitz et al., 2001). Higher microbially-labile organic matter contents also favor enhanced denitrification by providing substrate for heterotrophic denitrifier growth, which leads to more rapid O_2 consumption (Hill and Cardaci, 2004). High N_2O emission may also be favored in alkaline soils due to more suitable growth conditions for both nitrifiers and denitrifiers (Bárta et al., 2010; Tierling and Kuhlmann, 2018). Furthermore, agricultural practices, such as N fertilization, crop species, crop rotation and water management may have strong influences on N_2O emission (Kudo et al., 2014; Trost et al., 2016). Numerous studies have investigated the impacts of soil properties and agricultural practices on soil N_2O emissions in conservation tillage systems and found diverse and contradictory results that hinder the overall assessment of conservation tillage impacts on climate change mitigation. Previous meta-analyses have also examined various aspects of N_2O emissions from conservation tillage. Van Kessel et al. (2013) investigated changes in N_2O emission in response to different categorical conservation tillage practices and found strong influences from the duration of conservation practices and climate regimes. Their meta-analysis focused on the magnitude of N_2O emission under contrasting conservation tillage regimes, but did not consider specific soil properties (pH, texture and organic content) and widely-used agricultural practices (rotation, water and residue management). Zhao et al. (2016) analyzed the relationship between specific-conditions and greenhouse gas emissions in no-till farming systems using meta-regression based on a regional database in China, but this analysis was limited in scale.

A detailed assessment of the influence of conservation tillage practices on soil N_2O emission is critical to determine the potential for conservation tillage practices to mitigate climate change. This study aimed to assess the effects of conservation tillage on soil N_2O emission relative to conventional tillage by conducting a meta-analysis of peer-reviewed field studies. Specifically, we attempt to address the following questions: i) How do climate regime and experimental duration affect soil N_2O emissions following application of conservation tillage practices? ii) Do initial soil properties affect the response of N_2O emission to conservation tillage practices? and iii) Can agricultural practices mitigate N_2O emission associated with conservation tillage? This comprehensive meta-analysis is significant for developing strategies for the future expansion of conservation tillage and for enhancing agricultural practices to mitigate greenhouse gas emission from agricultural lands.

2. Materials and methods

2.1. Data collection

A comprehensive literature review was carried out in Web of Science to identify peer-reviewed articles with N_2O emissions comparisons for conservation tillage with conventional tillage in side-by-side paired field trials. Conservation tillage in this meta-analysis included no-tillage and reduced tillage practices, such as chisel tillage and shallow/lower depth tillage. The keywords 'tillage', 'nitrous oxide', 'N_2O', and 'greenhouse gas' were used as search terms. Specific criteria considered in selecting paired trials were: i) studies conducted in the field; ii) studies reported cumulative soil N_2O emissions (kg N_2O-N ha^{-1}) for at least one entire crop season duration for both conservation and conventional tillage treatments; iii) studies reported the mean and number of field replicates; and iv) studies for which N input rate was reported or could be accurately calculated. The data in most studies were reported in tables and extracted directly. For data presented in figures, 'GetData Graph Digitizer' software was used to extract data (Version 2.26: http://www.getdata-graph-digitizer.cm/download). According to the criteria listed above, a total of 212 comparisons from 40 field studies were available for the meta-analysis.

For each study, the cumulative emission of N_2O (kg N_2O-N ha^{-1}), number of replicates and standard deviations (SD) for both conservation and conventional treatments were extracted directly. Unit conversion was performed as necessary, such as global warming potential (GWP of 298 for N_2O) and the N_2O emission was reported as kg N_2O ha^{-1}. The SD was computed when only the standard error (SE) was reported:

$$SD = SE \times \sqrt{n}$$

where n is the number of replicates. The SD value was assigned as 20% and 21% for conservation and conventional tillage, respectively, in studies where SD/SE was absent, as these values were the relative averages of the reported SD values for N_2O emission in our dataset (Skinner et al., 2014).

In addition to N_2O emission data, other related information for each study was also included in the dataset: location (longitude and latitude), climate (annual precipitation and temperature), experimental duration, crop species, soil properties (*e.g.*, texture, pH, clay content, SOC), and agricultural practices (crop rotation, residue management, water management and N fertilization rate). For studies not reporting the climate information, we estimated the missing data from Wikipedia in accordance with site locations.

2.2. Data analysis

We conducted a random-effects meta-analysis to assess N_2O emission under conservation tillage versus conventional tillage. The natural log of the response ratio ($\ln R$) was calculated in each paired trial to compare the effect size of N_2O emission between conservation and conventional tillage.

$$\ln R = \ln\left(\frac{X_t}{X_c}\right) = \ln(X_t) - \ln(X_c)$$

where X_t is the mean value of N_2O emission with conservation tillage and X_c is the mean value of N_2O emission in conventional tillage as control.

The variance of $\ln R$ (V) for each study was estimated:

$$V = \left(\frac{SD_t^2}{n_t X_t^2}\right) + \left(\frac{SD_c^2}{n_c X_c^2}\right)$$

where SD_t and SD_c are the standard deviations of all comparisons in the conservation and conventional tillage groups; and n_t and n_c are the number of replicates for the treatment and control groups, respectively.

The meta-analysis was conducted using a nonparametric weighting function, and the mean weighted effect size was calculated as:

$$\overline{\ln R} = \frac{\sum (\ln R_i \times \omega_i)}{\sum \omega_i}$$

where $\ln R_i$ was the effect size of N_2O emission in the ith comparison,

Table 1
Categorical variables, number of observations for NT/RT and CT amendments (n), various levels in each categorical variable (L), between-group heterogeneity (Q_B) in the random-categorical meta-analysis.

	Variable	n	L1	L2	L3	L4	L5	Q_B
Experimental conditions	Climate Zone	212	Warm temperate	Cool temperate	Tropical			26.3*
	Duration (year)	212	≤3	3-10	> 10			8.1*
Soil properties	pH	179	≤6.5	6.5-7.3	> 7.3			9.8*
	SOC (g kg^{-1})	171	≤15	15-30	> 30			3.4
	Soil texture	164	Coarse	Medium	Fine			4.4
	Clay content (%)	91	≤20	> 20				13.3*
Agricultural practice	N application rate (kg ha^{-1})	212	≤150	150-250	≥250			13.3*
	Crop type	200	Wheat	Rice	Maize	Bean	Others	17.4*
	Rotation	212	Rotation	No rotation				5.1*
	Residue management	205	Residue retained	Residue moved				20.6*
	Water management	164	Irrigated	Rain-fed				9.5*
	Tillage management	212	Reduced tillage	No-tillage				0.5

Note:
* Represents significance level of 0.05.

and ω_i was the weight calculated as:

$$\omega = \frac{1}{V}$$

where V is the variance of ln$R$ as stated above.

This meta-analysis was specifically designed to explore the influence of soil properties, climate regimes and agricultural practices on N_2O emission in conservation tillage systems. Thus, the variables were separated into different categories consisting of 3 groups that included 12 categorical variables selected to determine the effect size of N_2O emission under conservation tillage relative to conventional tillage. Each variable was separated into several levels. For example, according to the climate zone classification of IPCC, climate regimes were divided into warm temperate, cool temperate and tropical (Maillard & Angers, 2014); N application rate was grouped into ≤150, 150–250 and ≥250 kg ha^{-1}; and residue management into residue retained or residue moved. Detailed information for different levels in each categorical variable is provided in Table 1. A categorical randomized-effects meta-analysis model was developed to compare the categorical mean effect size and determine any significant differences among categorical groups. Total heterogeneity (Q_T) for each variable was partitioned into two parts, within-group heterogeneity (Q_W) and between-group heterogeneity (Q_B) using chi-square distributions. Correspondingly, conservation tillage has a significant effect when different categories within each variable have a significant Q_B.

We calculated overall mean effect size and generated 95% bootstrapped confidence intervals (CIs, 4999 interactions) in METAWIN 2.1 software (Rosenberg et al., 2000). The effect size was considered significant if the 95% CI did not overlap with the zero value. To improve explanatory power, the mean effect size was transformed back to the percentage change of N_2O emission for conservation tillage relative to conventional tillage and was computed as $((e^{\overline{\ln R}}-1)\times 100\%)$.

Here we defined an additional N_2O emission factor (EF_{ad}), which is the conservation tillage-induced change in N_2O emission compared to conventional tillage when N fertilizer is applied. The conservation tillage-induced EF_{ad} was calculated as:

$$EF_{ad}(\%) = (X_t - X_c)/N \times 100$$

where N is the N application rate (kg N ha^{-1}).

3. Results

3.1. Effect of conservation tillage versus conventional tillage on soil N_2O emissions

The continuous randomized-effects model identified significant relationships between effect sizes of N_2O emissions under conservation tillage versus precipitation and N fertilizer application rate (Table 2).

Table 2
Relationships between the effect size of soil N_2O emission under conservation tillage relative to conventional tillage for climate conditions (precipitation and temperature), soil properties (pH, SOC, TN, clay, bulk density) and N application rate. A continuous random-effects model was used to calculate statistical results, including total heterogeneity among studies (Q_T), the heterogeneity explained by regression model (Q_M), and residual error heterogeneity (Q_E). Significant relationships were identified as p value < 0.05.

Variable	Q_T	Q_M	Q_E	Slope	p	n
Precipitation	263.9	4.0	259.9	−0.0002	0.046*	212
Temperature	250.5	2.9	247.6	0.0107	0.086	212
pH	257.1	0.2	256.9	−0.0136	0.663	178
SOC	255.8	0.2	255.6	0.0013	0.618	170
TN	196.8	2.0	194.8	−0.0315	0.158	147
Clay	136.9	0.2	136.7	−0.0013	0.640	90
Bulk Density	182.3	0.7	181.6	−0.2549	0.270	107
N application rate	278.5	5.5	273.0	0.0008	0.019*	211

Effect size was negatively correlated with precipitation and positively correlated with N application rate. The effect size was not correlated with temperature, soil pH, SOC, TN, clay content or bulk density. The significant correlation with precipitation ($p = 0.046$) and near significant level with temperature ($p = 0.086$) demonstrate the site-specific conditions associated with climate in affecting N_2O emission in conservation tillage systems.

Overall, the mean effect size of soil N_2O emission for conservation tillage versus conventional tillage was 17.8% (95% CI: 9.6–27.3%). Conservation tillage was mainly divided into two categories, no-tillage and reduced tillage. No-tillage showed a significant increase in soil N_2O emission as compared to conventional tillage (average: 19.2%, 95% CI: 9.3–29.8%), while no significant effect was observed in the reduced tillage systems (average: 12.3%, 95% CI: −0.5–31.7%) (Fig. 1a). However, the categorical randomized-effects model showed no significant differences in soil N_2O emissions for the two conservation tillage systems compared to conventional tillage ($p = 0.552$). In contrast, the categorical randomized-effects model showed a significant difference between climate regimes ($p < 0.001$, Fig. 1b). Soil N_2O emissions were significantly higher in the tropical climate (average: 74.1%, 95% CI: 34.8–119.9%) and warm temperate climate (average: 17.0%, 95% CI: 6.5–29.2%). In contrast, there was no significant difference for soil N_2O emissions between conservation tillage and conventional tillage (average: -1.7%, 95% CI: -10.5–8.4%) in the cool temperate climate.

The effect size of conservation tillage on N_2O emission was also dependent on the duration of the field trial as indicated by the significant differences among various levels of experimental duration (Fig. 2a). Compared to conventional tillage, the incremental increase in soil N_2O emissions from application of conservation tillage generally

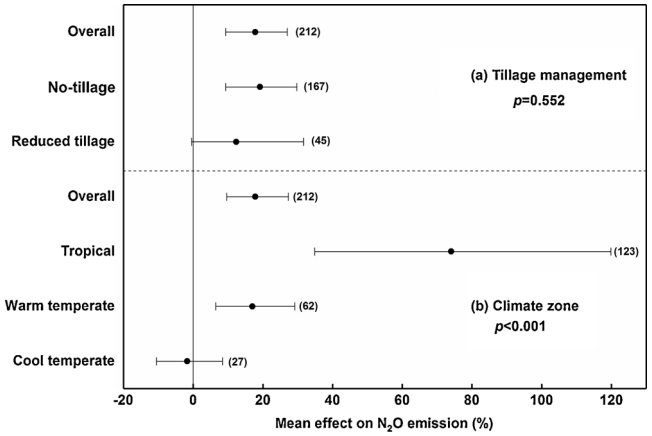

Fig. 1. Effect of tillage management (a) and climate regime (b) on soil N_2O emission following application of conservation tillage management (mean ± 95% confidence interval; number of observations in parentheses). A significant effect was observed when there was no overlap with the zero value; significant difference was identified between various levels with a p value < 0.05.

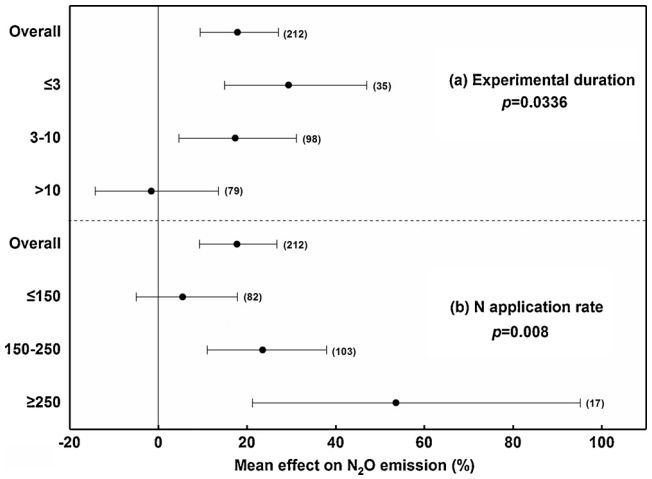

Fig. 2. Effect of conservation tillage duration (a) and N application rate effect (b) on soil N_2O emission following application of conservation tillage management (mean ± 95% confidence interval; number of observations in parentheses). A significant effect was observed when there was no overlap with the zero value; significant difference was identified between various levels with a p value < 0.05.

decreased with increasing experimental duration. Notably, significantly elevated N_2O emissions were indicated for studies with short (≤3 yrs, average: 29.3%, 95% CI: 14.9–47.0%) and medium term duration (3–10 yrs: average: 17.3%, 95% CI: 4.6–31.1%). There was no significant difference in N_2O emissions for long-term (> 10 yrs) application of conservation tillage (average: 1.6%, 95% CI: -14.3–13.5%). Additionally, the N_2O emission effect size showed a significant increase with increasing N application rates (p = 0.008, Fig. 2b). While no significant change in soil N_2O emission was observed at application rates ≤150 kg ha^{-1} (average: 5.5%, 95% CI: -5.0–17.8%), significant increases were identified for N application rates of 150–250 (average: 23.5%, 95% CI: 11.0–37.9%) and ≥250 kg ha^{-1} (average: 53.6%, 95% CI: 21.22–95.15%).

Soil properties played an important role in soil N_2O emissions (Fig. 3). Though non-significant (p = 0.337), there were some apparent characteristic trends in the mean effect size within SOC categories. In general, the average stimulation of conservation tillage-induced soil N_2O emission increased with increasing SOC (Fig. 3a). On average, conservation tillage significantly increased soil N_2O emissions by 12.0% (95% CI: 1.3–24.5%) in the SOC range of 15-30 g kg^{-1} and by 22.0%

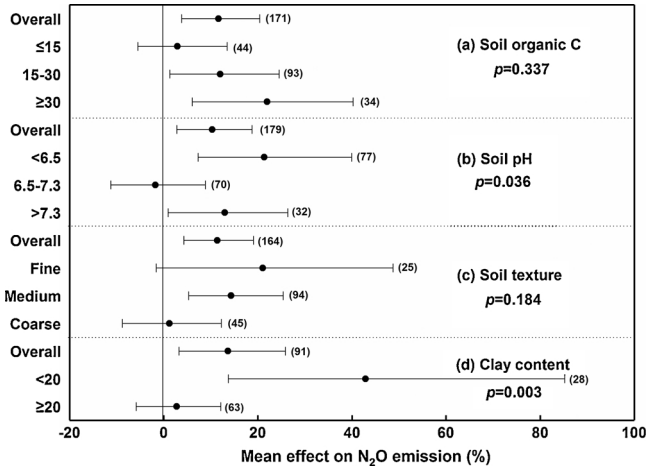

Fig. 3. Effect of soil organic C (a), pH (b) and texture (c) on soil N_2O emission following application of conservation tillage management (mean ± 95% confidence interval; number of observations in parentheses). A significant effect was observed when there was no overlap with the zero value; significant difference was identified between various levels with a p value < 0.05.

(95% CI: 6.1–40.3%) when SOC exceeded 30 g kg^{-1}. Soil pH significantly affected soil N_2O emissions after adoption of conservation tillage compared to conventional tillage (p = 0.036, Fig. 3b). Conservation tillage significantly increased soil N_2O emissions by an average of 21.3% (95% CI: 7.3–39.9%) in acidic soils and 13.0% (95% CI: 0.9–26.4 %) in alkaline soils. However, there was no significant change in soil N_2O emissions at neutral soil pH levels (average: -1.8%, 95% CI: -11.3–8.8%). Soil texture significantly affected soil N_2O emissions for conservation tillage versus conventional tillage in medium-textured soils (average: 14.3%, 95% CI: 5.3–25.4%), but not in fine-textured (average: 21.1%, 95% CI: -1.6–48.7%) or coarse-textured (average: 1.23%, 95% CI: -8.76-12.22%) soils (Fig. 3c). Clay content showed a significant effect on soil N_2O emissions (p = 0.003, Fig. 3d) at clay contents < 20% resulting in a 42.9% stimulation in soil N_2O emissions (95% CI: 13.7–85.2%), while no effect was evident when clay content exceeded 20% (average: 2.7%, 95% CI: -7.0–13.5%).

Agricultural practices within conservation tillage systems further altered soil N_2O emissions (Fig. 4). There was a significant but highly variable response of N_2O emissions between different water management practices (p = 0.003, Fig. 4a). Soil N_2O emissions under rain-fed

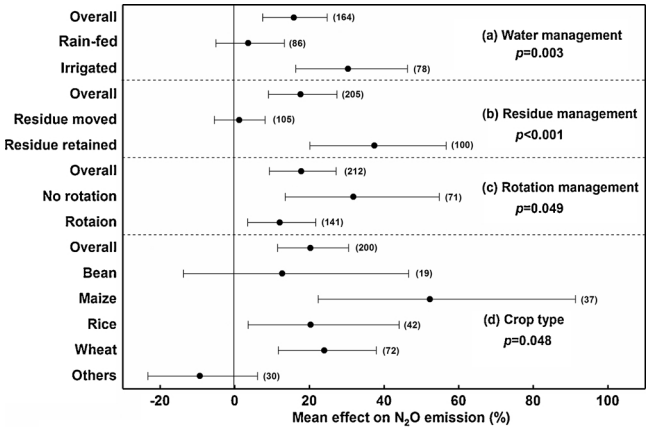

Fig. 4. Effect of water management (a), residue management (b), rotation management (c) and crop type (d) on soil N_2O emission following application of conservation tillage management (mean ± 95% confidence interval; number of observations in parentheses). A significant effect was observed when there was no overlap with the zero value; significant difference was identified between various levels with a p value < 0.05.

systems were enhanced by 3.6% (95% CI: -5.1–13.3%) by conservation tillage relative to conventional tillage and by 30.4% (95% CI: 16.3–46.3%) under irrigation water management. Similarly, residue management significantly affected soil N_2O emissions in conservation tillage ($p < 0.001$, Fig. 4b). Conservation tillage induced soil N_2O emission increased by 31.8% (95% CI: 13.5–54.8%) for non-rotation systems compared to a 12.1% (95% CI: 3.5–21.7%) increase for crop rotation systems (Fig. 4c). Conservation tillage induced soil N_2O emission varied significantly among various cropping systems when compared to conventional tillage ($p = 0.048$, Fig. 4d). Three of five investigated crop species were identified to promote soil N_2O emissions in conservation versus conventional tillage systems. The highest stimulation of N_2O emission was associated with maize (average: 52.3%, 95% CI: 22.3–91.1%), followed by wheat (average: 20.4%, 95% CI: 11.7–37.9%) and rice (average: 20.3%, 95% CI: 3.6–44.1%). In contrast, no significant differences were recorded for beans and other cropping system (*e.g.*, vegetables).

3.2. Additional soil N_2O emission factors

Overall, the average conservation tillage-induced N_2O emission factors (EF_{ad}) (additional N_2O contributed by conservation tillage relative to conventional tillage as control) was 0.40% (Fig. 5). There was no significant difference in EF_{ad} between no-tillage (1.32%) and reduced tillage (0.23%) systems ($p = 0.400$, Fig. 5a). The conservation tillage-induced EF_{ad} showed significant differences among climate zones with average EF_{ad} in tropical climates (1.54%) being significantly higher than in warm (0.15%) and cool temperate (0.08%) climates. No significant differences were observed as a function of soil texture (medium = 0.24%, fine = 0.18%, coarse = 0.06%) or for rotation (0.34%) versus no rotation (0.23%) management. Retention of crop residues was associated with higher EF_{ad} (0.51%) than residue removal (0.11%). Additionally, the EF_{ad} following application of conservation tillage showed a higher EF_{ad} in irrigated (0.55%) versus rain-fed (0.18%) agricultural systems. Regardless of conservation tillage category, the EF_{ad} showed a significant negative correlation with duration of the applied conservation practice when residue was moved (Fig. 6a),

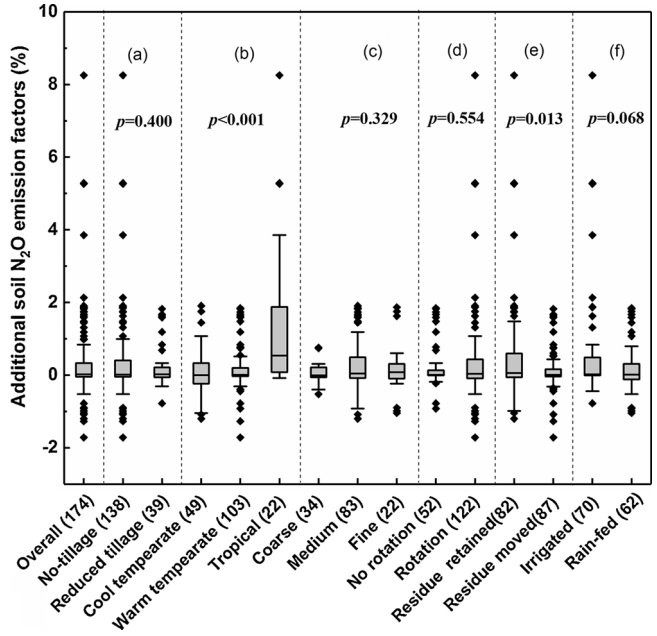

Fig. 5. Boxplots of additional soil N_2O emission factors (EF_{ad}, %) for conservation tillage application for different categories of conservation tillage (a), climate regime (b), soil texture (c), rotation management (d), residue management (e), and water management (f). Significant differences were recorded at $p < 0.05$.

which indicates a diminishing influence of conservation tillage on soil N_2O emission with increasing time. The decreased N_2O emissions with duration of conservation tillage was more pronounced for reduced tillage systems than for no-tillage systems, which was consistent with the EF_{ad} value. According to the relationship, the effect of no-tillage and reduced tillage practices on enhancing the EF_{ad} would dissipate after 7 and 17 years, respectively. The regulating influence of soil property was enhanced when residue was retained, especially with respect to soil texture (Fig. 6b). A strong positive correlation was observed between EF_{ad} and silt content in no-tillage systems ($n = 26$, $R^2 = 0.156$, $p = 0.046$). According to the identified relationships among these variables, at silt contents greater than 22.3%, no-tillage systems would have a positive EF_{ad} compared to conventional tillage and vice versa. A positive correlation was also detected between EF_{ad} and soil clay content in reduced tillage systems. When soil clay content reached 15.8%, reduced tillage management resulted in a positive EF_{ad} relative to conventional tillage and vice versa.

4. Discussion

Conservation tillage is promoted as an effective method for carbon sequestration and thus a possible mitigation strategy for climate change (Lal, 2004). However, considerable controversy exists concerning how conservation tillage affects soil N_2O emissions, which may offset potential carbon-related climate change mitigation benefits (Antle and Ogle, 2012). N_2O emissions are primarily controlled by the microbiological processes of nitrification and denitrification. Whereas the heterotrophic denitrification process occurs under anaerobic conditions, nitrification is an aerobic process (Stevens et al., 1997). Therefore, the integrated effects of soil physical, chemical and biological factors, such as soil aeration, pH, temperature, moisture, texture and substrate availability, function together to affect soil N_2O emission dynamics. Furthermore, agricultural practices, such as irrigation, fertilization and cropping systems, play important direct/indirect roles in soil N_2O emissions. Given the wide range of integrative factors affecting N_2O emissions, a comprehensive meta-analysis can provide a powerful approach for gaining important insights into the importance of specific factors regulating N_2O emission across a wide range of spatial and temporal scales.

4.1. Effects of conservation tillage on soil N_2O emission

Overall, the implementation of conservation tillage significantly affected soil N_2O emission in this meta-analysis (Fig. 2); however, non-significant differences were observed for different conservation tillage practices. These results are consistent with an analysis by Van Kessel et al. (2013). Meta-regression results indicated some detailed information concerning differences in no-tillage versus reduced tillage practices on soil N_2O emission. At the initiation of conservation tillage, soil compaction can moderate soil aeration and stimulate N_2O emission through denitrification. However, substrate limitation (due to the removal of residue) suppressed this initial stimulation leading to decreased N_2O emission over time (Rochette et al., 2008). With retention of residues, sufficient substrate (especially labile organic C forms) is available to support the N_2O-producing heterotrophic microbial community. With sufficient substrate availability, soil aeration becomes a dominant factor regulating N_2O emission in conservation tillage systems. As shown in Fig. 6b, N_2O emission rate was regulated by the interactions of conservation tillage and soil texture. N_2O emission in both conservation tillage practices displayed a significant positive correlation in the fine particle size classes (silt and clay), which was consistent with the higher N_2O emissions in fine-textured soils observed by Choudhary et al. (2002). Conservation tillage may improve bulk density and water holding capacity, especially in the fine-textured soils which are prone to generate anaerobic microsite hotspots for N_2O production in otherwise aerobic soils (Bouwman et al., 2002; Rochette,

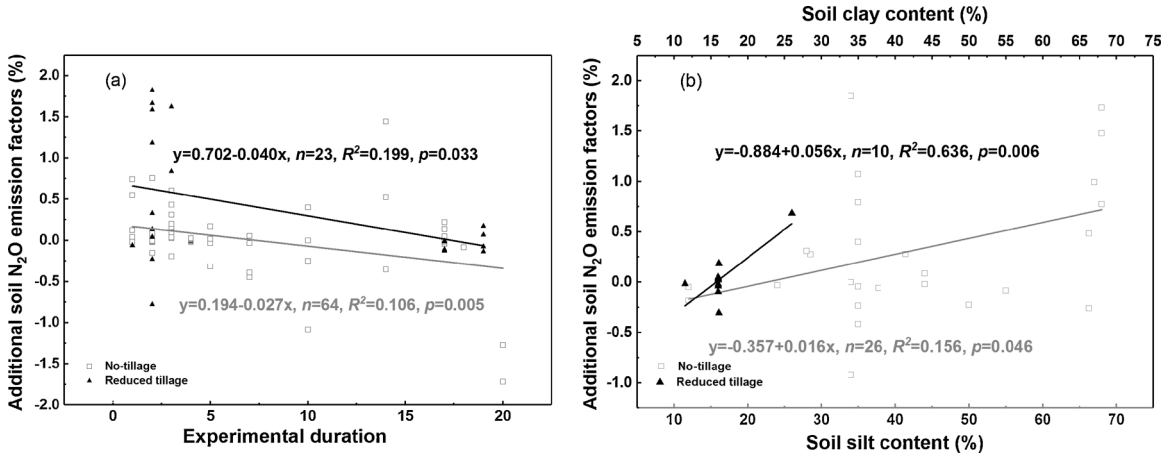

Fig. 6. Relationship between EF_{ad} and experimental duration (a, residue moved), soil prosperities (b, residue retained) under different conservation tillage categories compared to conventional tillage. A significant relationship was identified for $p < 0.05$.

2008).

4.2. Climate and duration effect on N_2O emission

Significant differences were recorded in conservation tillage induced soil N_2O emissions among climate regimes. Temperature and precipitation are the primary factors regulating N_2O emission across climate regimes. A significant negative correlation was recorded between effect size and precipitation (Table 2), consistent with the findings of Van Kessel et al. (2013) who reported a larger mean effect size in dry climates than humid climates upon implementation of reduced tillage. Increasing amounts of precipitation lead to higher soil moisture and lower soil oxygen concentrations, which strongly regulate nitrification and denitrification dynamics. Higher water-fill pore space (WFPS) was observed in no-tillage systems compared to conventional tillage during the dry season, but no difference was observed during the normal wet portion of the year (Venterea et al., 2006). WFPS differences were more pronounced between tillage practices under lower precipitation scenarios, which resulted from increased denitrification-induced N_2O emission in conservation tillage relative to conventional tillage. In addition, the N_2O emission effect size showed a weak positive correlation ($p = 0.086$) with temperature (Table 2), which was further supported by the higher increase of N_2O emissions in tropical and warm temperate climate regimes (Fig. 1b). These findings are similar to those found by Zhao et al. (2016). Nitrification is favored at optimal soil temperature and moisture conditions of 25–40 °C and WFPS of 30–70%, respectively. Within the optimal conditions, nitrifier activities are enhanced with increasing soil temperature leading to the potential for increased soil N_2O emissions (Hu et al., 2013). However, contradictory results have shown higher N_2O emissions from soils in conventional tillage versus no-tillage with increasing temperature (Tu and Li, 2017).

Conservation tillage-induced N_2O emissions were affected by experimental duration. Short- to medium-term implementation of conservation tillage significantly increased soil N_2O emission, especially in the first 3 years following the initiation of conservation tillage. However, a negative mean effect size was measured for studies with long-term experimental duration (> 10 years). Similar changes in N_2O emissions with duration of conservation tillage were reported by Six et al. (2010), with an increase of N_2O emissions in the first 10 years and a decrease thereafter. These changes associated with duration of conservation tillage may be attributed to attainment of new steady-state soil conditions, such as soil structure, compaction, WFPS and aeration, which are not optimal for soil microbes to produce N_2O by denitrification and/or nitrification processes.

4.3. Effects of initial soil properties on N_2O emission

Soil N_2O emissions are strongly correlated with soil denitrification-nitrification processes that are driven by soil microbes, which in turn are largely affected by several soil properties. SOC and generalized soil texture had no significant differences on N_2O emissions following implementation of conservation tillage. A trend of increasing N_2O emission with increasing SOC content was reported by Li et al. (2005). High SOC provides more substrate for heterotrophic denitrifiers, which should favor enhanced denitrification and N_2O emissions (Russenes et al., 2016). Soil texture strongly affects soil aeration and thus is often implicated as an important factor regulating N_2O emissions. As nitrification is considered to be the dominant process generating N_2O in generally well aerated, coarse-textured soils (Zhou et al., 2013), application of conservation tillage in these soils may result in soil compaction and poor aeration, suppressing nitrification and its associated N_2O emissions. In contrast, denitrification is often the primary N_2O-generating process in fine-textured soils due to a generally higher prevalence of anoxic microsites (Gu et al., 2013). Therefore, application of conservation tillage to fine-textured soils may result in the development of additional anaerobic conditions through compaction and greater water retention owing to the higher micropore content of compacted soils, which favor the development of additional anaerobic microsites for denitrification.

Soil pH and clay content were identified to significantly affect the N_2O emission effect size from the implementation of conservation tillage. Our analysis indicated a significant increase of N_2O emissions in acidic and alkaline soils but not in neutral soils. Greater N_2O emissions in acidic soils have been previously reported (Samad et al., 2016; Liu et al., 2010). In acidic soils, stepwise denitrification was purported to be suppressed by an attenuation of reductase (N_2OR) activities that hinder N_2O conversion to N_2, resulting in the accumulation of N_2O in acidic soils (Liu et al., 2014). In contrast, nitrifiers generally perform better in neutral to slightly alkaline soils (Sánchez-García et al., 2014), which may contribute to increased N_2O emissions in alkaline soils. The effect of clay content on N_2O emission in our analysis contradicts the expectations of increasing N_2O emission with increasing clay content (Chen et al., 2013). The significant increase of N_2O emission in soils with low clay content was mostly associated with medium-textured soils, which was consistent with the results of our soil texture evaluation. However, the sample size for low clay content soils was small, which could bias the results. More comparisons are necessary for a rigorous exploration of the effect of clay content on soil N_2O emission in conservation tillage systems.

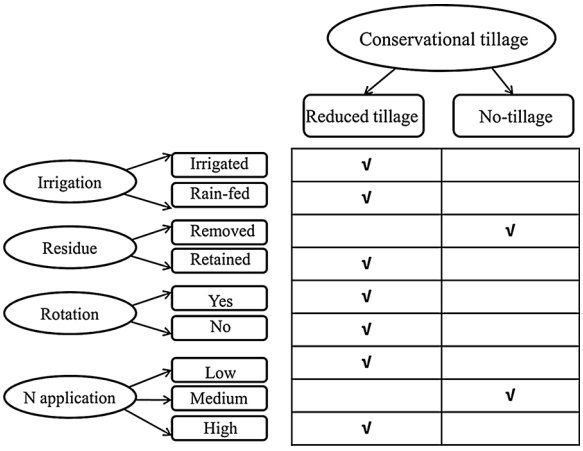

Fig. 7. Conservation tillage criteria for mitigation of additional soil N_2O emission. N application rate classified as Table 1.

4.4. Effect of agricultural practices on N_2O emission

As expected, increasing N application rates led to increased N_2O emissions (Fig. 2b, $p < 0.05$). Similar results were reported from short-term trials evaluating the influence of N application on N_2O emissions in Mediterranean soils (Plaza-Bonilla et al., 2014). Enhanced inorganic N from fertilization would be expected to intensify nitrification-denitrification processes resulting in increased N_2O production. A linear response of N_2O emission to N application rate was identified when the N fertilizer rate was less or equal to that required to achieve maximum crop yield, while an exponential increase in N_2O emission was observed in soils with higher N inputs (Halvorson et al., 2008; Van Groenigen et al., 2010).

Contrasting water management practices showed a significant influence on soil N_2O emission in conservation tillage systems (Fig. 4a). Irrigation significantly increased soil N_2O emissions, consistent with the findings of Cayuela et al. (2016). The drying and wetting cycles created by irrigation provide an ideal environment for coupled nitrification-denitrification. Nitrate production during the dry period is available for denitrification when irrigation increases the WFPS leading to potential anaerobic conditions (Shi et al., 2013).

A significant difference was found between residue retained and residue removed treatments following implementation of conservation tillage, consistent with the report by Baggs et al. (2003). Retention of residues provides substrate for microbial growth through mineralization, which should increase denitrifier and nitrifier abundance depending on oxygen content (Burger and Jackson, 2003). Inorganic N released from residue by mineralization would further stimulate the N_2O production processes. Finally, consumption of soil O_2 from enhanced organic matter decomposition may contribute to a greater prevalence of anaerobic conditions that favor denitrification (Chen et al., 2013).

Our analysis indicated that crop rotation reduced N_2O emission from conservation tillage as compared to non-rotation systems. Previously, no significant effect of crop rotation on N_2O emission was found by Omonode et al. (2011). As our analysis indicated a relatively weak significance level ($p = 0.049$) for crop rotation effects on soil N_2O emission dynamics, further investigations are warranted to better understand the complex interactions between crop rotation and N_2O emission.

Our meta-analysis showed a crop-specific effect on conservation tillage induced N_2O emissions (Fig. 4d). The higher N_2O emissions from maize, wheat and rice may be related to the higher N fertilizer application rates for these crops as compared to the lower and insignificant effects from beans and other crop types (mainly vegetables) that generally receive lower N fertilization rates. The relatively small increase of N_2O emissions determined in rice paddies following conservation tillage was similar to that reported by Zhang et al. (2015) and is possibly due to the dominance of anaerobic conditions that favor complete denitrification (conversion of N_2O to N_2) and thus a lower yield of N_2O relative to N_2.

5. Implications and conclusions

This meta-analysis, which assessed conservation tillage induced N_2O emissions, was based only on field trial results in order to provide conclusions deemed relevant to real-world field conditions. Conservation tillage practices have been reported to reduce CO_2 emissions by ~21% (Abdalla et al., 2016). However, application of conservation tillage significantly increased soil N_2O emission by ~17.8% compared to conventional tillage in our analysis, which offsets the potential climate change mitigation benefits associated with soil carbon sequestration. To provide guidance for minimizing the negative effects from N_2O emission, we synthesized the results from our EF_{ad} analysis to a criterion-based guide for minimizing the impacts of specific agricultural practices in reduced tillage and no-tillage systems on N_2O emissions (Fig. 7). Overall, reduced tillage (versus no-tillage) produced more favorable results and was advantageous regardless of rotation or water management practices. Only in the case of residue removal and medium application rates for N fertilizer did no-tillage result in less enhancement of N_2O emission compared to reduced tillage.

In summary, adoption of conservation tillage increased soil N_2O emission, especially for the no-tillage practice. IPCC estimated a 1.00% N_2O emission factor by fertilizer and an additional 0.40% emission of N_2O was determined from this meta-analysis. Enhanced conservation tillage induced N_2O emission was more prominent in tropical and warm temperate climates. The enhanced N_2O emissions diminished with increasing duration of conservation tillage, particularly after 10 years of application. Conservation tillage induced N_2O emissions were strongly affected by several initial soil properties (*e.g.*, pH and clay content) and agricultural practices (*e.g.*, water, residue and rotation management, and crop type). Based on this analysis, criteria to minimize N_2O emission were developed for reduced tillage and no-tillage systems. These criteria can assist agricultural land managers in minimizing the conservation tillage offsets of climate change mitigation due to enhanced N_2O emission.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi: https://doi.org/10.1016/j.still.2018.05.006.

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